

Forest floor temperature and relative humidity following timber harvesting in southern New England, USA

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Abstract

Forest amphibians, especially salamanders, prefer forests with shaded, cool, and moist forest floors. Timber harvesting opens the forest canopy and exposes the forest floor to direct sunlight, which can increase forest floor temperatures and reduce soil moisture. These microclimatic changes can potentially degrade the harvested stand for amphibian habitat or affect other biotic resources or ecological processes at the forest floor and in the understory. The degree of forest floor disturbance is directly related to the intensity of harvesting, however, the duration of this effect is unknown. We conducted a study of forest floor temperature and relative humidity over a 12-year chronosequence (1993–2004) of timber harvests. We compared simultaneous, paired measurements of temperature and relative humidity at three positions (soil, forest floor, air) in harvested and control sites over three seasonal survey sessions. Vegetation composition and structure were measured at each survey location. Ambient weather conditions were recorded at three open-field locations across the study area.

We recorded over 23,000 paired measures of temperature and relative humidity at all 12 harvested and control sites during each survey session. While we found significant effects of time-since-harvesting on differences in temperature between harvested and uncut sites, the average differences were generally small ($<1^{\circ}\text{C}$). We observed no temporal pattern in temperatures with time-since-harvest in the harvested sites compared to uncut conditions. Time-since-harvest had no effect on differences in relative humidity between cut and uncut sites. The variation in forest floor microclimate among sites was large, likely due to small-scale differences in cutting intensity (retained canopy), understory vegetation growth, and microtopography or aspect. We conclude that timber harvesting, within the range of intensities assessed in this study, would have only minimal and short-term effects on forest floor microclimate. We suggest that the small differences we observed in forest floor temperatures and moisture between cut and uncut forest parcels would likely have minor effects on climatic aspects of forest amphibian habitat, and on climatic influences on other forest floor biota and ecological processes.

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1. Introduction

A concern was raised about the effects of timber harvesting on forest floor temperature and moisture in the development and review of draft Massachusetts Conservation Management Practices (CMPs) for state-listed mole salamanders (*Ambystoma* spp.) (NHESP, 2006). As the name implies, mole salamanders inhabit and forage in the litter and humus soil horizons and on the forest floor during wet nights (DeGraaf and Yamasaki, 2001). While there was consensus in the discussion

of the draft CMPs that the removal of canopy trees and resultant exposure would increase forest floor temperatures and reduce soil moisture, there was little agreement on the relationship between the amount of stocking reduction and resultant changes in temperature and soil moisture. Further, there was no agreement on the duration of any forest floor effects as forest vegetation recovered following harvesting (Morris and Maret, 2007). No literature could be found to resolve this uncertainty and the final consensus CMPs called for the retention of 75% canopy cover of trees greater than 30 ft tall on 70% of an area 50–450 ft from a breeding site (NHESP, 2006).

While the guidelines were drafted for mole salamanders, forest floor microclimatic changes due to timber harvesting

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have been shown to have negative consequences for other taxa of salamanders, notably plethodontids (Pough et al., 1987; Petranksa et al., 1993; Ash and Bruce, 1994; Harper and Gynnn, 1999). The effects of timber harvesting on anurans has been less consistent (deMaynadier and Hunter, 1995; Ross et al., 2000). Forest floor temperatures and moisture are also important influences on forest floor biota and plant and soil processes (Spurr and Barnes, 1980; Chen et al., 1999). Forest soil temperature has received increased attention for its effects on soil carbon processes (Davidson et al., 1998; Barford et al., 2001; Gough et al., 2007).

The lack of adequate guiding literature for the decision on a canopy-retention standard prompted the authors to implement this study, but the study was not specifically designed to be a test of the standard. The objective of this study was to determine the temporal pattern in forest floor temperature and moisture following timber harvesting. We hypothesized that, due to the generally rapid growth of forest floor vegetation in the northeastern United States following canopy disturbance, forest floor temperatures and relative humidity would recover to pre-cut (control) conditions within only a few growing seasons. This dense regrowth of herbaceous and woody-stemmed plants following canopy disturbance would form a low insulating layer that would reduce temperatures and increase or maintain humidity levels at the forest floor in harvested areas (Weng et al., 2007).

In a study of forest microclimate in Ontario, MacHattie and McCormack (1961) found that forested sites had warmer (higher) monthly mean minimum growing-season air temperatures than cleared sites, regardless of topographic location, but the differences between the forested and cleared sites ranged between 1 and 2 °C. Comparable maximum temperatures were cooler in the forested site by about 4 °C, except for the more exposed south-aspect location. Whole-tree harvesting in an oak (*Quercus* spp. L.) forest in Virginia resulted in maximum 6–7 °C increase in average soil temperatures in July and August, compared to the adjacent uncut area (Johnson et al., 1985). Over the rest of the year, the differences were much less. Soil moisture was greater in the harvested area than in the uncut throughout the growing season due to a reduction in transpiration. Even-aged harvesting in a Wisconsin oak forest resulted in higher periodic maximum air temperatures and lower minimum temperatures than in an uncut forest (Yin and Perry, 1989). The average differences in the study were greatest in the recent shelterwood treatment (difference in maximum temperature 7.3 °C, minimum temperature 4.7 °C), where both the overstory and understory were removed. In an older clearcut, where there was a dense cover of shrubs and regenerating trees, the average difference in both maximum and minimum temperatures from the uncut site was only 1.9 °C.

In this study, we surveyed forest floor temperatures and relative humidity across a 12-year chronosequence of harvested lots. Harvests were principally group selection or patch cuts; no lot was clearcut. Temperature and relative humidity were simultaneously measured at three vertical positions (soil, forest floor, air) in harvested lots and in paired, adjacent uncut control sites. Microclimatic surveys were conducted at three locations

in each cut and control site during spring, summer, and fall survey sessions between May and October 2006. The response variable was the difference between paired measures of temperature or relative humidity in the cut and control locations (Chen et al., 1995; Potter et al., 2001).

2. Study area and methods

2.1. Study sites

The study was conducted on the Pelham and Prescott Management Blocks of the Quabbin Reservoir watershed (hereafter, Quabbin Reservation) (72°21'W, 42°17'N) in central Massachusetts (Fig. 1). The Reservoir is the principal source of water for metropolitan Boston and the property is managed by the Office of Watershed Management, Massachusetts Department of Conservation and Recreation (DCR). Much of the forest land is actively managed for a diverse, vigorous forest that is resistant to wind damage and other disturbances (O'Connor et al., 1995).

The forests of the Quabbin watershed are dominated by oaks and white pine (*Pinus strobus* L.) with lesser acreage of birch (*Betula* spp. L.), red maple (*Acer rubrum* L.), red pine (*P. resinosa* Ait.), eastern hemlock (*Tsuga canadensis* (L.) Carr.), and other northern hardwood species (O'Connor et al., 1995; Kyker-Snowman et al., 2007). The management of the Quabbin forests emphasizes both water yield and water quality. Silvicultural prescriptions emphasize shelterwood preparatory cuts to establish regeneration where it was missing, followed by single-tree and small group- or patch-cuts to create a multi-aged, species-diverse forest structure. This blending of even- and uneven-aged silvicultural practices meets the objectives for restoring regeneration and developing a forest structure that is resistant to or resilient following major disturbances such as wind, ice, diseases, or insects.

All harvested lots on the western side of the Quabbin watershed that had been cut since 1993 were identified to select 12 harvested lots for this study. Lots harvested prior to 1993

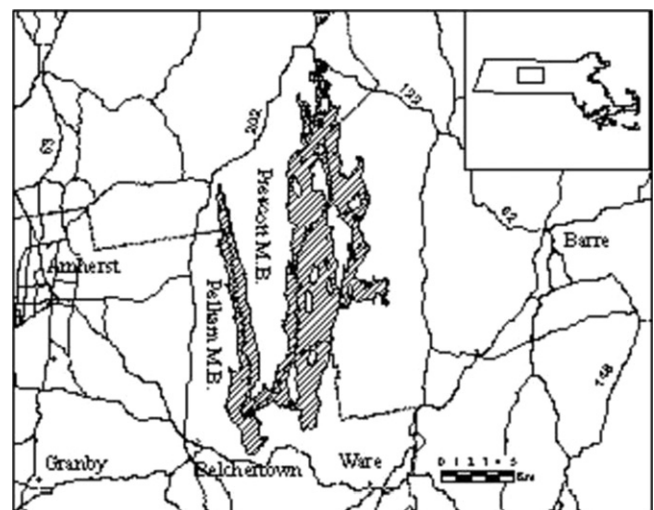


Fig. 1. Location of Pelham and Prescott Management Blocks relative to the Quabbin Reservoir, Massachusetts.

Table 1
Characteristics of study lots by age class, Quabbin Reservation, Massachusetts

Growing-season interval	Lot number	Number growing seasons	Size (ha)	Silvicultural system	Completion date
1	624	13	8.4	Irregular shelterwood	January 1993
1	667	12	10.1	Selection	March 1994
1	649	11	10.1	Selection	September 1994
2	661	9	14.6	Selection	March 1996
2	728	8	11.3	Selection	September 1997
2	774	7	6.5	Selection	March 1999
3	779	6	25.1	Selection	August 1999
3	819	5	10.9	Selection	December 2000
3	3003	4	10.9	Selection	July 2002
4	2008	3	13.4	Selection	December 2002
4	3045	2	21.4	Selection	February 2004
4	2014	1	23.5	Selection	October 2004

were excluded because white-tailed deer (*Odocoileus virginianus* Zimmermann) densities were exceptionally high at that time and regeneration following timber harvests was minimal. This problem was corrected when a controlled deer hunt was first implemented in 1991 (Barten et al., 1998). Deer densities on the Quabbin are now similar to those of regulated herds in rural, mainland Massachusetts (MassWildlife, 2006). The full list of harvested lots was initially screened to select lots that were predominantly oak or white pine and that had been harvested by a shelterwood or seed preparatory cut or a small-group or patch regeneration cut.

The selected lots were visited in the field to verify the species composition and treatment. Following field visits, a final screen removed all lots with large-scale eastern or northern aspects, to control for topographic influences on forest floor microclimate (MacHattie and McCormack, 1961). Choosing sites with south or west aspects allowed for maximum solar exposure and a rigorous assessment of the effects of canopy removal on forest floor microclimate. The final list of acceptable lots was sorted by year of treatment, a lot was randomly selected for each calendar year between 1993 and 2004, and the selected lots were assigned to one of four sequential, 3-year growing-season intervals (Table 1). The harvested lots ranged in area between 6.5 and 25.1 ha (Table 1) and were variously shaped, depending upon site and stand constraints and silvicultural objectives.

A paired, adjacent uncut control site was identified for each cut lot, either in the uncut portion of the same stand as the harvested lot or in an adjacent stand. The intent was to select control sites with the same forest conditions (e.g., composition, size class) as the cut lot had prior to harvest. We did not attempt to control for aspect or slope of the cut and associated control sites beyond the screening described previously.

2.2. Field methods

2.2.1. Temperature and relative humidity surveys

Replicate sample locations within each cut lot were randomly located either from a central transect or a central point, depending on whether the lot was longer in one direction

or compact. Central transects or points were identified using sketch maps drafted at the time of the timber sale. Initial sampling locations in each control site were subjectively chosen in the interior of the site to avoid edge effects, as stand maps were not available to randomize their placement. The selection of the exact, initial sampling point in the control sites was randomized by blindly tossing a flagged wire stake. Subsequent replicate sample locations in control sites were located at 20 m distances in a random direction from the previous location. In all cases, sampling locations were chosen to avoid edge conditions.

Temperature and relative humidity were measured over three sessions, corresponding to spring (8 May–1 June), summer (18 July–10 August), and fall (17 September–10 October) seasons, in each cut and control site. During each sampling session, temperature and relative humidity were measured simultaneously at three positions: 1 m above the ground (air), at the forest floor, and at the interface of the litter and humus soil layers (soil). Air measurements were taken using a HOBO[®] Pro RH/Temp Data Logger (Onset Computer Corporation, Pocasset, MA), soil measurements using an iButton Hygrochron[™] (Dallas Semiconductor, Dallas, TX), and forest floor measurements using either a HOBO or iButton, decided on the flip of a coin. Paired cut and control forest floor

Table 2

Mean differences (cut–control) in paired observations of (A) temperature (°C) and (B) relative humidity (%) by position, age class, and session, Quabbin Reservoir watershed, 2006 (positive values indicate that the cut sites were, on average, warmer or more humid than the uncut sites)

Position	Number of growing seasons	Session		
		Spring	Summer	Fall
(A) Mean temperature differences				
Soil	1–13	0.338	1.266	−0.031
	7–9	−0.732	0.836	0.139
	4–6	0.758	1.613	0.521
	1–3	0.572	0.209	−0.008
Forest floor	11–13	−0.027	0.018	−0.215
	7–9	−0.012	0.802	−0.155
	4–6	0.835	1.448	0.255
	1–3	0.233	0.261	−0.476
Air	11–13	−0.165	0.043	−0.215
	7–9	0.17	0.397	−0.02
	4–6	0.232	0.795	0.076
	1–3	0.113	0.042	−0.189
(B) Mean differences in relative humidity				
Soil	11–13	−0.025	−0.006	0.047
	7–9	0.001	<0.001	<0.001
	4–6	−0.001	−0.001	−0.005
	1–3	−0.001	0.001	<0.001
Forest floor	11–13	0.396	0.019	0.002
	7–9	−0.005	−1.099	−0.003
	4–6	0.032	−0.707	0.037
	1–3	0.004	0.333	0.353
Air	11–13	0.003	0.049	0.253
	7–9	<0.001	−0.007	0.05
	4–6	0.03	−0.228	0.17
	1–3	−0.002	0.312	0.021

measurements were always taken using the same type of equipment. Air and forest floor units were suspended from a wooden stake to insure their fixed position. To minimize direct solar heating, these units were shielded with a piece of painted aluminum flashing and the stake was placed so the units were oriented to the north. This allowed for the measurement of ambient conditions and precluded potentially differential heating of the differently sized and colored iButtons and HOBOs. For ease of recovery, soil iButtons were placed in small mesh envelopes before being placed in the ground. Soil locations were unshielded and exposed to full solar radiation.

Data loggers were programmed to record temperature and relative humidity every 15 min. Data loggers were installed before noon on the first day of a session and removed 8 days (seven nights) later. As we were only able to purchase 12 of each device, we sampled four paired cut and control sites at a time. By removing and installing the units on consecutive days, we could sample all 12 paired sites within 24 days (three 8-day periods). The schedule for sampling individual paired sites within each growing-season interval was randomized for each session.

Ambient weather (temperature, precipitation) data were collected at three open-field sites during the survey sessions. At two sites, Onset[®] tipping-bucket rain gauges and temperature data loggers were used; data from the third site came from the DCR's permanent Quabbin weather station in Belchertown, MA. The three weather stations are roughly located along a central north-south axis on the Quabbin that spans the distribution of the study sites.

2.2.2. Vegetation surveys

Vegetation composition and structure were measured at each survey location ($n = 3$) in each harvested and control site to be able to describe the impact of harvesting. Vegetation surveys were conducted while the data loggers were installed at each site. Woody-stemmed vegetation was measured on nested, fixed-radius, circular plots centered on the stake supporting the forest floor and air data loggers. Stems ≥ 25 cm in height to 2.49 cm in diameter at breast height (dbh) were counted on 0.001 ha plots by species; species and dbh of stems 2.5–9.9 cm diameter were individually enumerated on 0.01 ha plots; and similarly for stems ≥ 10 cm diameter on 0.025 ha plots. Percent cover of ground vegetation (herbaceous and woody-stemmed less than 25 cm tall) and of slash/coarse woody debris cover was estimated to the nearest 5% on circular 0.04 ha plots. Canopy cover of trees ≥ 10 m tall was measured using a concave, spherical densiometer, with four measurements taken in cardinal directions at each sample point. Canopy closure was measured over a larger area with a “moosehorn” densiometer, with 10 sightings taken at about 1 m intervals on each of eight evenly spaced transects radiating out from the sample point, for a total of 80 sightings per location. With these two methods, we were trying to capture the distinction made by Jennings et al. (1999), who defined canopy cover as the “area of the ground covered by a vertical projection of the canopy” and canopy closure as “the proportion of the sky hemisphere obscured by vegetation when viewed from a single point.”

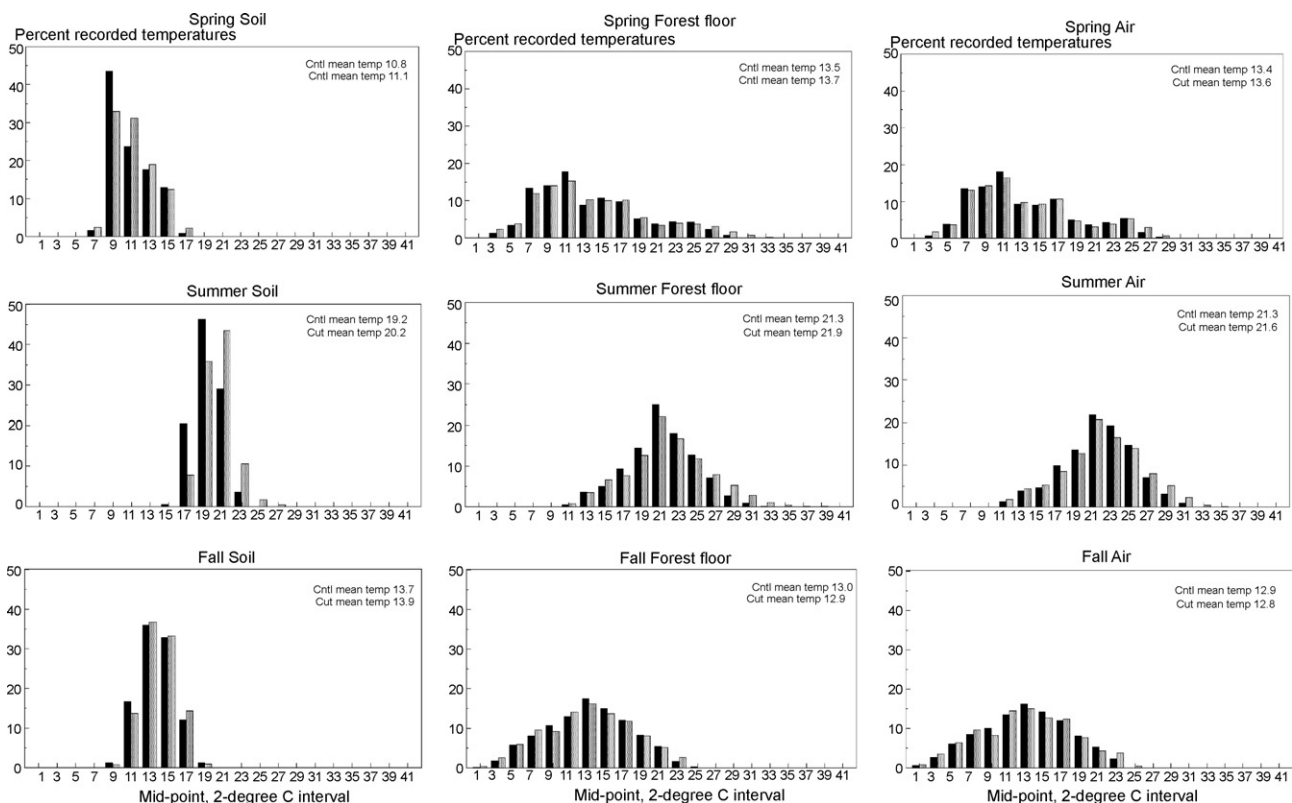


Fig. 2. Distribution of recorded temperatures and mean temperatures by treatment (control: solid bars; cut: stippled bars), position, and session, Quabbin Reservation, Massachusetts, 2006.

Table 3

Average daily (A) maximum and minimum temperatures (°C) and (B) relative humidity (%) by age class, session (season), position, and treatment, Quabbin Reservation, 2006

Number of growing seasons	Temperature	Soil		Forest floor		Air	
		Control	Cut	Control	Cut	Control	Cut
(A) Average daily temperatures							
Spring							
11–13	Maximum	11.3	12.2	18.2	19.7	18.4	19.1
	Minimum	9.7	9.7	8.9	8.3	9.0	8.3
7–9	Maximum	12.7	11.8	20.2	20.9	18.7	19.4
	Minimum	10.4	9.8	9.4	9.3	9.5	9.5
4–6	Maximum	11.6	12.8	18.8	23.6	18.7	20.8
	Minimum	10.0	10.4	9.3	8.7	9.4	8.6
1–3	Maximum	11.9	12.9	11.9	12.9	18.8	19.5
	Minimum	10.1	10.3	9.2	8.4	9.3	9.0
Summer							
11–13	Maximum	19.3	21.3	26.4	29.0	26.2	27.9
	Minimum	17.3	18.2	16.1	16.2	16.4	16.3
7–9	Maximum	20.5	21.3	26.7	28.1	26.2	27.4
	Minimum	18.4	19.0	16.8	16.8	17.2	17.1
4–6	Maximum	20.3	22.3	25.7	30.9	26.4	29.5
	Minimum	18.2	19.4	16.6	16.6	16.7	16.6
1–3	Maximum	20.8	21.5	26.8	30.3	26.2	28.3
	Minimum	18.7	18.7	17.3	16.3	17.3	16.1
Fall							
11–13	Maximum	14.5	14.4	18.1	18.5	18.4	18.6
	Minimum	12.5	12.6	8.1	7.7	7.6	7.4
7–9	Maximum	15.3	15.1	19.8	19.6	18.8	19.3
	Minimum	12.5	12.8	8.5	8.4	8.1	7.9
4–6	Maximum	14.7	16.4	17.9	20.7	18.5	20.8
	Minimum	12.6	12.8	8.4	8.2	7.9	7.4
1–3	Maximum	15.0	14.9	19.6	19.0	18.7	18.9
	Minimum	12.7	12.8	9.2	8.5	8.9	8.4
Number of growing seasons	Soil	Forest floor		Air			
	Control	Cut	Control	Cut	Control	Cut	
(B) Relative humidity							
Spring							
11–13	100.0	100.0	92.7	95.6	91.9	92.3	
7–9	100.0	100.0	93.5	93.1	88.8	88.8	
4–6	100.0	100.0	91.9	92.9	88.3	89.4	
1–3	100.0	100.0	90.9	91.2	88.1	87.8	
Summer							
11–13	100.0	100.0	96.8	97.2	94.5	95.4	
7–9	100.0	100.0	97.9	93.9	93.0	92.6	
4–6	100.0	100.0	95.8	91.8	94.2	91.8	
1–3	100.0	100.0	90.2	93.4	87.4	90.8	
Fall							
11–13	100.0	100.0	97.9	98.0	93.9	96.1	
7–9	100.0	100.0	98.0	97.8	93.9	94.9	
4–6	100.0	100.0	96.6	97.3	93.7	95.6	
1–3	100.0	100.0	93.5	96.1	89.9	90.8	

2.3. Analysis

Temperature and relative humidity data were classified by quarter day: night (00:01–06:00 h), morning (06:01–12:00 h), afternoon (12:01–18:00 h), and evening (18:01–24:00 h) to control for diurnal patterns, especially in temperature (Yang et al., 2007). The effect of time-since-harvest (number of growing seasons) on forest temperature and relative humidity was analyzed with repeated-measures, analysis of variance of the difference between simultaneous, paired measurements of treatment and control data (Chen et al., 1995; Potter et al., 2001). Growing-season intervals and quarter day were classified as fixed effects, lot within growing-season interval as a random effect. A separate analysis was conducted for each position (soil, forest floor, air). All percent data (relative humidity, ground and slash cover, canopy cover and closure) were arcsine transformed prior to analysis (Zar, 1974: 185).

3. Results

3.1. Microclimate temperature and relative humidity

Over 650 paired measurements of harvested and control site temperatures and relative humidity were recorded by each data logger at each of the 12 sites and three positions (air, forest floor, soil) over the 8-day survey sessions. The compiled database has three repeats of 23,633 paired temperature and relative humidity measurements, representing the spring, summer, and fall survey sessions.

3.1.1. Temperature

Differences between paired measures of temperature in cut and uncut locations were small, typically averaging less than 1 °C (Table 2A). The largest differences in temperature occurred in the afternoons of the summer session: 2.1 °C in soil, 3.9 °C at forest floor, and 2.3 °C in air positions. Temperatures were most often warmer at harvested sites in spring and summer sessions (Table 2A). In fall, the reverse was true, and control sites were more often warmer than harvested sites. The effect of time-since-harvest (growing season interval) on differences between cut and control temperatures were significant for soil ($F_{df=3,8} = 4.298$, $p(F) \sim 0.0458$) and forest floor positions ($F_{df=3,8} = 5.44$, $p(F) \sim 0.025$), and not significant for the air position ($F_{df=3,8} = 2.23$, $p(F) > 0.1$). Effects of season, time of day (quarter day), and site within growing-season interval on temperature differences were significant ($p < 0.05$) at all positions.

All temperatures exhibited expected daily and seasonal patterns. Temperatures were coolest in the spring and fall and warmest in the summer across all treatments and positions (Fig. 2). The range in recorded temperatures was greatest in the summer session and, marginally greater at the forest floor compared to the air temperatures (Fig. 2). Maximum recorded temperatures occurred in harvested lot 819 in the afternoon of 18 July 2006, reaching 27.6 °C at the soil position, 42.5 °C at the forest floor, and 36.6 °C at the air position. The average maximum ambient temperature on that date was 34.3 °C.

Table 4
Average vegetation structure by treatment and age class, Quabbin Reservation, 2006

Number of growing seasons	Harvested sites						Uncut, control sites					
	Basal area (m ² /ha)	Stem density (#/ha)	Canopy		Cover		Basal area (m ² /ha)	Stem density (#/ha)	Canopy		Cover	
			Cover (%)	Closure (%)	Ground (%)	Slash (%)			Cover (%)	Closure (%)	Ground (%)	Slash (%)
11–13	29.6	50,411	50.8	47.5	24.2	1.4	49.2	16,180	96.6	95.5	18.1	1.4
7–9	24.5	40,778	84.5	63.4	8.0	4.6	29.3	10,191	95.5	90.6	24.1	3.9
4–6	23.8	58,132	55.0	50.4	19.6	10.2	40.3	16,258	94.7	93.7	32.5	8.0
1–3	14.2	34,482	61.8	52.3	31.3	2.5	34.0	42,836	98.3	94.4	11.5	1.4

Highest average maximum daily temperatures occurred in cut sites with four to six growing seasons at all positions in the summer session (Table 3A). The range in maximum daily temperatures among growing-season intervals was only 1 °C at the soil position, 2.8 °C at the forest floor, and 2.1 °C at the air. Daily maximum summer temperatures at control sites averaged 1.4 °C less than cut sites at soil, 3.2 °C at forest floor, and 2 °C at air positions.

Temperature patterns differed among positions (Fig. 2). In both control and harvested sites, soil temperatures were generally cooler and less variable than those at the forest floor or in the air, except in the fall session, when soil temperatures were often warmer than forest floor and air temperatures. Forest floor and air temperatures were similar in each season.

3.1.2. Relative humidity

Differences in paired measurements of relative humidity between cut and control sites were not significant for the effects of time-since-harvest at all positions ($F_{df=3,8} < 1.0$, $p(F) > 0.1$). Average differences in relative humidity between paired control and harvest sites were quite small, generally less than 1% (Table 2B). The effect of time of day on relative humidity differences was only significant ($F_{df=3,24} = 12.591$, $0.005 > p(F)$) at forest floor locations. Variation in humidity among sites within growing-season interval was significant at all positions.

The largest average differences in relative humidity occurred at the forest floor position in the afternoon of the summer session surveys; with the control site humidity measures exceeding harvested site values by an average of 3.9% in lots with four to six growing seasons since harvest. In spring, uncut sites were moister than harvested sites; in fall, the relationship was reversed. In summer, measures of relative humidity in harvested and control sites were roughly equivalent.

Average daily percent relative humidity was consistently 100% in soil positions for all seasons and growing-season intervals in both harvested and uncut sites (Table 3B). Average daily percent relative humidity was consistently higher at forest floor sampling positions than at air positions, but in all cases, the averages were near or greater than 90%.

3.2. Vegetation structure and composition

Basal area of trees greater than 2.5 cm dbh was reduced in harvested lots, compared to uncut, control sites, while the density of these and smaller-diameter trees, increased compared to comparable controls (Table 4). There was a general pattern of increase in basal area with time-since-harvest, but the density of residual and new growth stems did not respond in a linear fashion to increasing numbers of growing seasons (Table 4). While canopy cover and closure were less in cut sites than in paired uncut sites, they did not conform to an expected pattern of increasing canopy closure with time-since-harvest (Table 4). Ground and slash cover were highly variable in all lots and did not correspond to time-since-harvest.

3.3. Ambient weather

Average, ambient mean daily temperatures increased from spring (14.3 °C) to summer (22.5 °C) sessions and then decreased in the fall (13.6 °C) session (Table 5). The spring value is slightly cooler than the long-term (30 years) average for May and June (16.5 °C, Amherst, MA) while the summer and fall averages are slightly warmer than the long-term average of 21.1 and 12.8 °C, respectively (NOAA, 2004). A similar seasonal pattern was observed for average daily maximum and minimum temperatures. The highest recorded average daily maximum temperature (32.2 °C) occurred during the summer

Table 5
Total precipitation (cm) and average daily mean/maximum/minimum temperatures (°C) by session and week, Quabbin Reservation, 2006

Weather attribute	Spring session week			Summer session week			Fall session week		
	1	2	3	1	2	3	1	2	3
Total precipitation	7.39	5.66	0.38	2.03	1.9	0.98	0.72	6.11	0.29
Mean daily temperature	9.46	11.34	21.49	21.11	24.36	20.74	17.34	11.36	11.06
Maximum daily temperature	11.3	16.51	29.01	27.24	31.88	29.0	23.8	17.42	19.54
Minimum daily temperature	7.63	6.16	13.97	14.99	16.84	12.48	10.89	5.3	2.58

session and the lowest minimum (3.0 °C) during the fall session.

Precipitation events occurred on 15 of the 24 days in the spring session and on 6 of 24 days in summer and fall sessions. Precipitation amounts totaled 13.4, 4.9, and 7.1 cm over spring, summer, and fall survey sessions, respectively (Table 5).

4. Discussion

We examined differences in temperature and relative humidity between 12 randomly chosen, paired cut and uncut sites on the Quabbin Reservoir watershed in central Massachusetts (Fig. 1 and Table 1). Timber harvests had occurred over 12 years prior to the study. Sites were assigned to one of four classes, depending on the number of growing seasons that had occurred since harvest (Table 1). Data were recorded at three positions (soil, forest floor, air), at random locations in each site during three seasonal surveys between May and October 2006.

Differences in temperatures between cut and uncut locations were significantly affected by time-since-harvesting (growing-season interval), but the magnitude of the differences was small, generally less than 1 °C for all classes of results (Table 2A). Additionally, temperature differences did not diminish with time-since-harvest as hypothesized. The largest differences in soil temperatures were recorded in lots with four to six prior growing seasons, followed by the oldest lots (11–13 growing seasons), the youngest (1–3 seasons), and finally, the second oldest (7–9 seasons) (Tables 1 and 2A). The largest average temperature differences at both the forest floor and air positions were also recorded in lots with four to six growing seasons, followed in order of the magnitude of absolute difference by those with 7–9, 11–13, and 1–3 growing seasons.

All temperatures exhibited expected daily and seasonal temporal patterns, with highest maximum temperatures recorded during the summer session (Fig. 2). The highest maximum summer temperatures were recorded at forest floor positions, but these were only marginally higher than air temperatures. Maximum soil temperatures were lower than above ground temperatures, and minimum soil temperatures were higher than those recorded above ground during all sessions (Fig. 2). Ranges in recorded temperatures were slightly greater among harvested lots than control sites, especially in the summer session (Fig. 2), reflecting the greater diversity in vegetation structure in harvested lots.

Maximum daily temperatures rarely exceeded published critical thermal maximum for spotted salamanders (38 °C; Pough and Wilson, 1970) or wood frogs (34.8 °C; Brattstrom, 1963). Only 67 recorded temperatures exceeded 34.8 °C in the harvested lots, from more than 71,000 temperature records, and only one recorded temperature exceeded 34.8 °C in the uncut sites (Fig. 2). All but 8 of the 67 extreme temperatures in the harvested lots came from one location in one lot, a bare patch with a pronounced southwestern aspect. Extreme high temperatures were recorded mostly at the forest floor and never at the soil positions (Fig. 2). Extreme maximum temperatures were clearly not a common or widespread occurrence. It seems unlikely that the occurrence of extreme

maximum temperatures would create detrimental conditions for mole salamanders, even in the most recently harvested lots.

Relative humidity measurements were high at all positions, in all surveys. Average daily relative humidity measurements in the soil were consistently 100% and above 90% at the forest floor position. As with temperature, the largest absolute difference in relative humidity between harvested and control sites occurred in the summer session at all positions (Table 2B). Time-since-harvest had no significant effect ($p > 0.1$) on differences in relative humidity between cut and paired uncut locations at any position. The only consistently significant effect on relative humidity was variation among locations and sites, demonstrating the high spatial variation in forest floor microclimate.

Recommended upland forest habitat for amphibians, and especially salamanders, is cool, moist forest floor conditions (Feder, 1983; deMaynadier and Hunter, 1995, 1999; Rittenhouse et al., 2004; Baldwin et al., 2006). Concerns have been expressed that timber harvests and full or partial removal of forest canopy exposes the forest floor and results in drier and warmer conditions than may be ideal for forest amphibians (Petranka et al., 1993, 1994; deMaynadier and Hunter, 1995; Knapp et al., 2003; Patrick et al., 2006; Morris and Maret, 2007). Baldwin et al. (2006) reported that the locations of radio-tagged wood frogs had lower percent canopy openness than near or far non-locations, but the differences were $\leq 2.1\%$ and, apparently, not significant. However, rapid growth of understory vegetation (e.g., herbaceous species, shrubs, regenerating trees) may create microclimatic conditions that promote the restoration of forest floor habitat and create acceptable conditions for amphibian use (Ash, 1997; Brooks, 1999, 2001; Rittenhouse et al., 2004).

Reports of forest floor microclimate and amphibian habitat conditions following timber harvests are sparse, but the consensus seems to be that there is little difference in temperatures or moisture between uncut and harvested sites. In a study of plethodontid salamander response to harvesting in the Missouri Ozarks, Herbeck and Larsen (1998) found a significant difference only in humus moisture between harvested and second-growth sites. Soil and humus moisture were greater in regenerating, cut sites than in either old-growth or second-cut sites, likely due to reduced transpiration. In a study of recently metamorphosed mole salamanders (*A. talpoideum*), Chazel and Niewiarowski (1988) found no difference in minimum or maximum soil temperatures between clearcut and uncut loblolly pine forests in South Carolina. Likewise, Rothermel and Semlitsch (2002) reported no significant difference in mean soil temperature or relative humidity between field and forest sites in a study of the dispersal of juvenile amphibians in Missouri. In a later study of juvenile ambystomid survival at the same study area, Rothermel and Semlitsch (2006) reported that only mean daily maximum temperatures differed significantly among forest, edge, and open field sites, and only in 1 year of a 2-year study. No significant differences were found in mean minimum daily temperature or mean or minimum soil moisture. In South Carolina, Rothermel and Luhring (2005) found higher mean

and maximum temperatures in clearcuts and thinnings than in uncut controls, but differences among habitat treatments were about 2 °C for each statistic.

We have shown that partial timber harvests, such as those used in this study, have minimal immediate and no apparent lasting effects on measures of forest floor temperature and relative humidity. Timber harvests included in the study were mostly uneven-aged, group selection or patch cuts and, on average, reduced basal area in the youngest cut lots (one to three growing seasons) to about 40% of the basal area of comparable control locations and canopy cover and closure to about 60% of control locations (Table 4), residual conditions more reduced than is typical for uneven-aged regeneration harvests (Smith, 1962). For comparison to other timber harvests in the study area, Kittredge et al. (2003) summarized harvesting intensities in the North Quabbin Region of Massachusetts, including most of the Quabbin study area, for the years 1984–2000 and concluded that harvests across the region on average removed approximately 27% of the stocking. The harvests in the review were described as selective harvesting of commercially valuable timber, rather than with silvicultural methods. Quabbin harvesting was conducted using silvicultural prescriptions designed to increase resistance and resilience of the forest canopy in the watershed protection forest. In general, the harvesting that was sampled in this study was more intensive than the average for the state or the region, and removed a broader range of species, sizes, and quality of timber and cordwood (Kittredge et al., 2003). Based solely on this comparison, one would expect that timber harvesting occurring in other central Massachusetts forests would have even less effect on forest floor microclimate.

If timber harvests in this study had occurred near vernal pools, residual conditions in cut lots would generally violate the Massachusetts Conservation Management Practices for state-listed mole salamanders, which require the retention of 75% canopy cover on 70% of life-zone habitat (NHESP, 2006). Nevertheless, differences in temperature and relative humidity between the cut and control sites, while statistically significant, were small (Table 2A) and unlikely to be biologically significant. The most severe temperatures, which occurred during summer afternoons (Table 3A), may affect salamander activity, but it is likely that forest salamanders would be in subterranean refuges at this time of the year (Semlitsch, 1981; Faccio, 2003; Rothermel and Luhring, 2005). The study was implemented almost 2 months following the peak of amphibian surface activity associated with spring migrations to breeding pools (approximately 1 April; Paton et al., 2000), we would expect even smaller differences in microclimate between cut and control locations in early spring, prior to tree leaf development. Nevertheless, effects of minor, but chronic increases in temperature on amphibians and on their ability to behaviorally or physiologically thermoregulate to these changed conditions is complicated and not well understood (Duellman and Trueb, 1994).

Other studies have found that forest amphibians, including spotted salamanders, can persist in partially harvested forests (Chazel and Niewiarowski, 1988; Brooks, 1999, 2001; Russell

et al., 2002; Perkins and Hunter, 2006) and possibly, after only a short regeneration period, following clear-cutting (Morris and Maret, 2007). Effects of timber harvesting on forest floor temperature and relative humidity associated with time-since-harvest in this study were vastly outweighed by variation among locations and sites, probably due to the spatial variability in the intensity of harvesting, resulting forest structure, and in micro-topography at the sampling sites (Jackson and Newman, 1967). It appears that partial timber harvests, within the limits of this study (Table 4), do not create forest floor microclimatic conditions sufficiently different from uncut forests to be biologically significant. Rapid growth of forest floor vegetation, both herbaceous and woody-stemmed, following harvesting and the retention of partial canopy cover would appear to create insulating layers that buffer the forest floor from increased solar exposure (deMaynadier and Hunter, 1999; Weng et al., 2007).

5. Conclusions

Based on the findings of this study, partial, selection-based timber harvests do not appear to create temperature and humidity conditions that would seriously vary from optimal forest amphibian habitat. Judged solely from these results, it would appear that required canopy retention practices of Massachusetts mole salamander Conservation Management Practices may be overly restrictive. However, effects of small, but chronic changes in forest floor microclimate on other attributes of forest amphibian habitat and biology, such as predator and prey abundance, the abundance of small mammal burrows, and of the ability of amphibians to thermoregulate to these changes, would need to be considered before such an assessment could be made.

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